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Survey of Commercial Small Lithium Polymer Batteries

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The power and energy of small 1 to 5 g lithium polymer batteries is improving significantly, with a push from the toy and hobby markets. This report characterizes the power and energy of several small batteries from Atomic Workshop, Full River, Kokam, and TOBN, presenting discharge curves as a function of C-rates. The 130 mAh Atomic Workshop batteries are rated to a specific power of nearly 2400 W/kg, and energies on the order of 140 to 160 Wh/kg. The Full River lithium polymer batteries also have high power and energy. The battery chemistry is the standard lithium cobalt oxide vs. carbon, so the high power is attributed to improvements in manufacturing.

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1. Introduction

Rechargeable small Li-ion or Li-polymer batteries are in wide demand for portable electronics. More recently, the toy and hobby market has introduced small lithium-ion batteries weighing 2 to 5 g. These commercial off the shelf (COTS) lithium-ion batteries may be useful for new military applications that also require small power sources that provide several Watts. The specific motivation for this study was to determine the suitability of COTS small Li-ion batteries for 10-g nanoair vehicles (NAVs), which require about 4 to 8 W for both propulsion and communications, but the findings are generic to a range of devices. Because the power to weight ratio is most important for air vehicles, we focus here on the metrics of specific power (W/kg) and specific energy (Wh/kg).

2. Definitions and background

The rate of doing work, *power*, or alternatively the energy or work produced or consumed per unit time, is expressed in this report in watts (W). Electrical power (P) in watts is the product of current (I) in amperes multiplied by the potential drop across the load (V) in volts.

$$P = I \ V$$

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The amount of work done, *energy*, is calculated from the time integral of the power.

$$E = \int P(t)dt$$

The amount of energy can be expressed in units of watt-hours (Wh) where 1 Wh of energy is equal to 1 W of average power integrated over a 1 hour period and is equal to 3600 J.

Rechargeable batteries are electrochemical energy storage devices that convert the chemical energy of stored inactive materials into electrical energy. In the case of Li-ion batteries, an individual electrochemical cell comprises a carbon-based negative electrode (anode) and a lithium-metal-oxide-based positive electrode (cathode), each of which has different electrical potentials, and are electronically separated but ionically connected with an electrolyte. The active material in the cathode is typically lithium cobalt oxide ($LiCoO_2$), or a nickel and manganese-based derivative, and the anode is typically a graphitic carbon which accommodates lithium intercalation. The active materials are additionally mixed with a polymer binder and a highly conductive carbon, to reduce ohmic losses. Slurries are formed by organic solvents mixed with these ingredients and are cast as thin films on aluminum (cathode) and copper (anode) current collectors. The separator is a microporous polymer membrane, such as Celgard and is wetted by a liquid electrolyte which is made conductive for Li ions by the addition of a salt such as lithium hexafluorophosphate ($LiPF_6$). The electrolyte is often gelled in small batteries to facilitate packaging and offers flexibility in the shape of the cell. These so-called Li-polymer batteries are functionally equivalent to Li-ion cells.

The practical capacity of a battery is determined by the amount of time needed to discharge between the starting voltage and the cutoff voltage at a particular current. Typical Li-ion batteries with $LiCoO_2$ and carbon are discharged galvanostatically from 4.1 V to 2.8 V. When discharged to voltages much lower, the $LiCoO_2$-based cell loses its reversibility partly because of instability in the $LiCoO_2$ crystal structure.

The energy of a battery is a function of the lithium capacity of the active materials. The theoretical specific capacity (expressed in mAh/g) of the battery materials can be easily calculated, using the following equation, where *n* is the number of moles of electrons stored per mole of material, M.W. is its molecular weight, and F is the Faraday constant (96,485 C/mol).

$$\text{specific capacity } \left({}^{\text{mAh}}\!/_{\text{g}} \right) = \frac{\text{n}}{3.6 \text{ M.W.}} \text{F}$$

The theoretical specific capacity of $LiCoO_2$ is about 140 mAh/g and that for Li_1C_6, is 340 mAh/g. The amount of active material in the cathode and anode must be balanced, and during discharge, the $LiCoO_2$ is the source of Li, and the carbon is the recipient, which forms Li_1C_6 when intercalated with Li ions. Thus, only one material can be considered an energy source. When a practical battery is assembled, the weights of the inactive current collectors, electrolyte, binders, and packaging add to the total weight of the battery but contribute no energy. Thus, the specific capacity and energy of a fully assembled, practical Li-ion battery is about 40 mAh/g, or 150 Wh/kg, respectively, assuming an average potential of 3.8 V. The smaller the battery is, the greater the penalty there is for inactive materials, particularly packaging, to the specific energy.

Each Li-ion battery is rated with a capacity, e.g., 50 mAh, and is expected to operate down to 2.8 V. This capacity may not be realized if the discharge current is too great. Consumption of this great a power results in decreased capacity because of I^2R heating, or ohmic losses, from the resistance of the materials in the cell. The I^2R losses are reflected in the cell operational voltage. While a $LiCoO_2/C$ cell has a discharge plateau of 3.8 V under very low currents, it can be as low as 3.0 V at higher currents, with 0.8 V lost due to resistance (proportional to Ohm's Law). This 0.8 V voltage drop would lead to a very short range for battery discharge (3.0 to 2.8 V), and thus low energy. The resistive losses can become significant at high power.

Ohmic losses can be decreased for high power applications mainly through cell manufacturing. The electrode resistance can be decreased with increasing area, A, and decreasing thickness, d, even as its materials resistivity, ρ, remains constant.

$$R = \rho \frac{d}{A}$$

The manufacture of thin, large-area electrodes requires specialized expertise in milling fine materials and electrode mixing and coating. Other factors in the cell resistance are the electrolyte conductivity, the morphology, and intrinsic conductivity of the active materials.

A relevant metric for charging and discharging batteries is the "C-rate", where 1C is the current needed to fully discharge a battery in 1 hour. Thus, a fully discharged 50 mAh battery, should be charged in 1 hour at a charge rate of 50 mA. Its C/5 rate should be about 10 mA while the 10C rate is 500 mA. The same approach is used to estimate discharge rates, as is done in this report. The exact time needed for charge and discharge will change with current, based on its ohmic losses, as discussed above.

3. Experimental

Small Li-ion batteries from Atomic Workshop, Full River, Kokam, and TOBN were purchased from various vendors, as listed in Table 1, at a cost of \$6 to \$10 per battery. Each battery was weighed, photographed, and then cycled (charged and discharged repeatedly) between 4.1 and 2.8 V under constant currents using a Maccor 2300 battery tester. After four charge and discharge cycles at the C/5 rate, as determined by the rated capacity of the battery, the cells were charged at C/5 and discharged at various rates between 1C and 20C in increasing order.

A nominal voltage for each discharge curve was determined from the voltage value (y value) at the midpoint of the discharge capacity (x value). The voltages were obtained with an error of ±1%. Capacities were determined as the discharge capacity at the 2.8 V cut off voltage. Power was estimated as simply the product of the current and nominal voltage for each discharge curve. The energy was estimated as the product of the nominal voltage and the capacity, ignoring any losses seen from the shape of the discharge curve. The specific energy and specific power denoted in the tables were the energy and power divided by the weight of the packaged battery, respectively.

Small batteries from Kokam, Atomic Workshop and Full River were disassembled to understand their chemistry, morphology, and manufacturing methods. The batteries were first discharged and then the packaging was cut open in a glove box. The cells were removed and unraveled before being introduced into the ambient air. The active materials in the cathodes and anodes were analyzed by X-ray diffraction (XRD, Bruker

D8 Advance), scanning electron microscopy (SEM, Leo Supra 55), and energy dispersive spectroscopy (EDS).

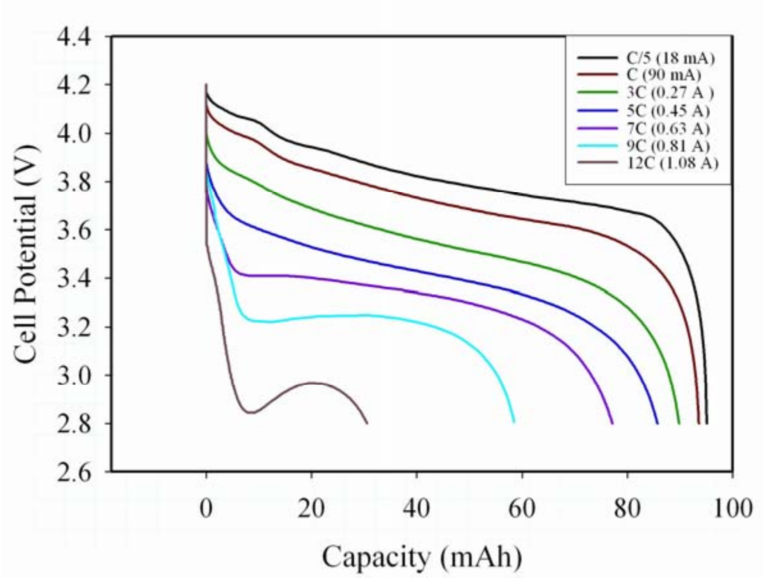
Table I. Power and weights of COTS batteries evaluated for this report.

BATTERY TYPE	Weight (g)	VENDOR SITE
Atomic Workshop 90 mAh	2.5	http://www.atomicworkshop.co.uk/
Atomic Workshop 130 mAh	3.6	"
Atomic Workshop 200 mAh	4.7	"
TOBN 80 mAh	3.3	http://www.tobnbattery.com/
TOBN 150 mAh	4.5	"
Full River 20 mAh	0.8	http://airmidimicros.com/AMMBatt.htm
Full River 50 mAh	1.6	http://www.bsdmicrorc.com/products.cfm?catID=10001
Kokam 145 mAh	4.2	http://www.kokam.com/english/product/battery_main.html

4. Results

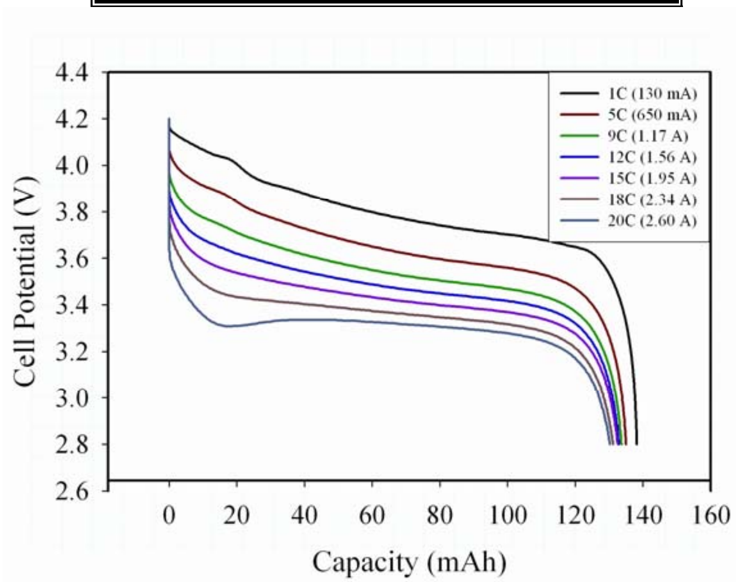
The results for the batteries in Table I are given below.

4a. Atomic Workshop 90 mAh, 2.5 g Li polymer battery



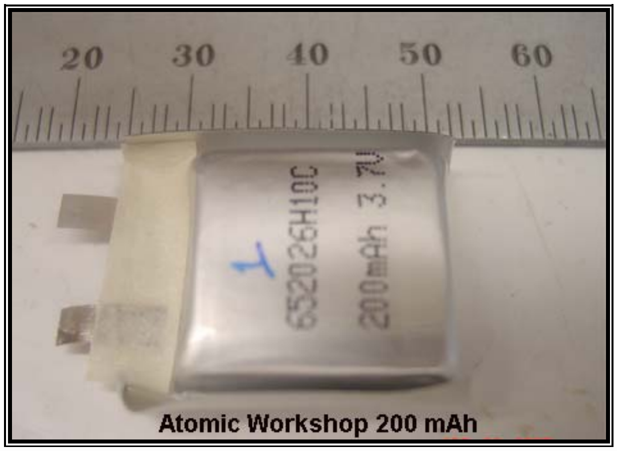
C-rate	Current (A)	Voltage	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp.Energy (Wh/kg)	Sp Power (W/kg)
1	0.09	3.72	93	0.3	346	1245	127	123
3	0.27	3.55	90	1.0	320	1150	117	351
5	0.45	3.42	86	1.5	294	1059	108	564
7	0.63	3.35	79	2.1	265	953	97	773
9	0.81	3.20	60	2.6	192	691	70	949
12	1.08	2.90	30	3.1	87	313	32	1147

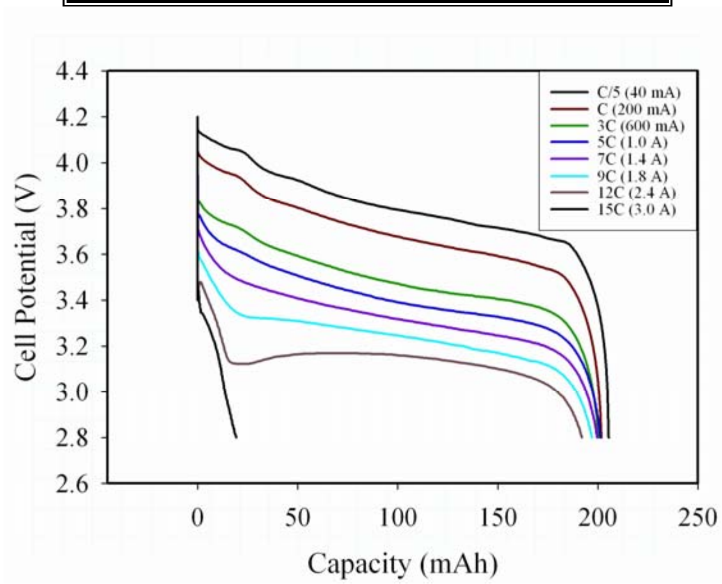
4b. Atomic Workshop 130 mAh, 3.6 g Li polymer battery



C-rate	Current (A)	Voltage	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp. Energy (Wh/kg)	Sp. Power (W/kg)
1	0.13	3.78	138	0.5	522	1905	145	137
5	0.65	3.64	135	2.4	491	1782	137	657
9	1.17	3.4	133	4.0	452	1628	126	1105
12	1.56	3.43	134	5.4	460	1654	128	1486
15	1.95	3.4	133	6.6	452	1627	126	1842
18	2.34	3.375	131	7.9	442	1591	123	2194
20	2.6	3.3	130	8.6	429	1544	119	2383

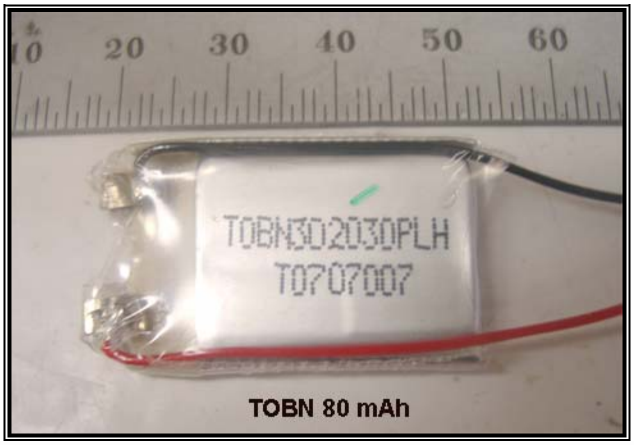
4c. Atomic workshop 200 mAh, 4.7 g Li polymer battery

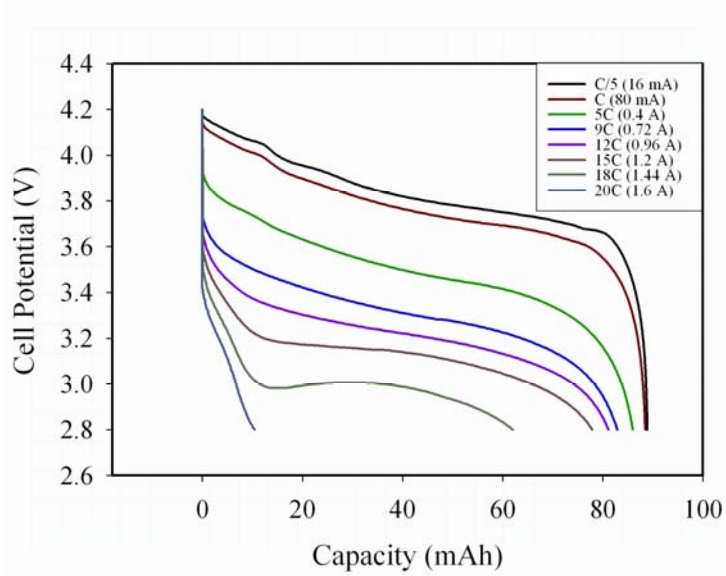




C-rate	Current (A)	Voltage (V)	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp. Energy (Wh/kg)	Sp. Power (W/kg)
1	0.2	3.70	202	0.7	747	2741	159	157
3	0.6	3.48	201	2.1	699	2532	149	443
5	1	3.40	201	3.4	683	2460	145	722
7	1.4	3.30	200	4.6	660	2426	140	981
9	1.8	3.26	197	5.9	642	2333	136	1246
12	2.4	3.20	192	7.7	614	2211	130	1631
15	3	0.00	0	0.0	0	0	0	0

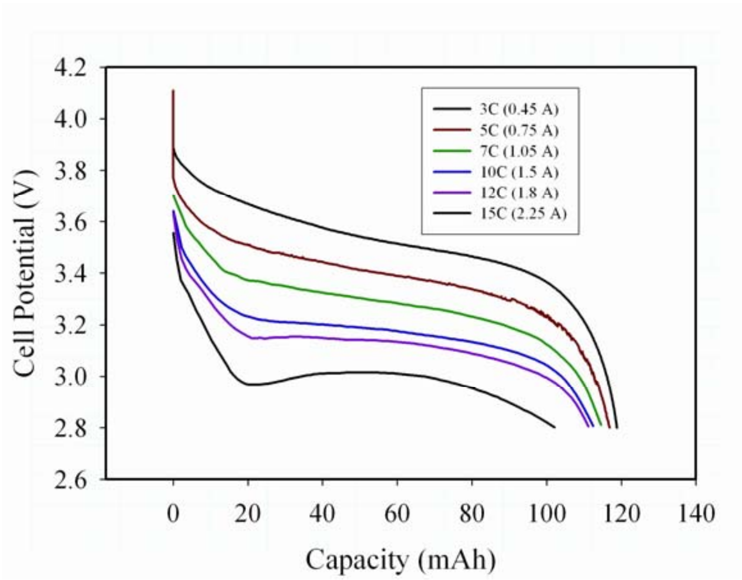
4d. TOBN 80 mAh, 3.3 g Li polymer battery





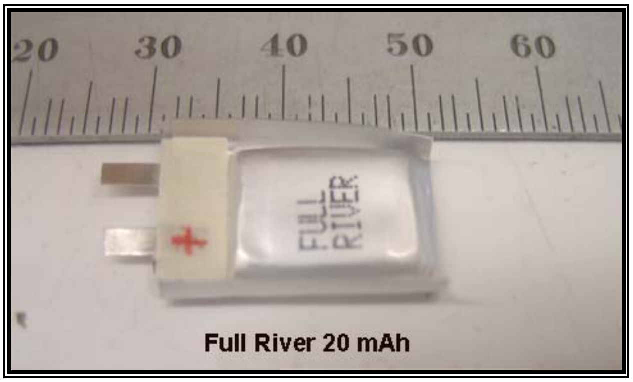
C-rate	Current (A)	Voltage	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp. Energy (Wh/kg)	Sp. Power (W/kg)
1	0.08	3.75	89	0.3	334	1201	108	97
5	0.4	3.48	86	1.4	299	1077	97	449
9	0.72	3.30	83	2.4	274	986	88	766
12	0.96	3.20	81	3.1	259	947	84	991
15	1.2	3.14	78	3.8	245	891	79	1215
18	1.44	3.00	62	4.3	186	670	60	1394
20	1.6	0.00	10	0.0	0	0	0	0

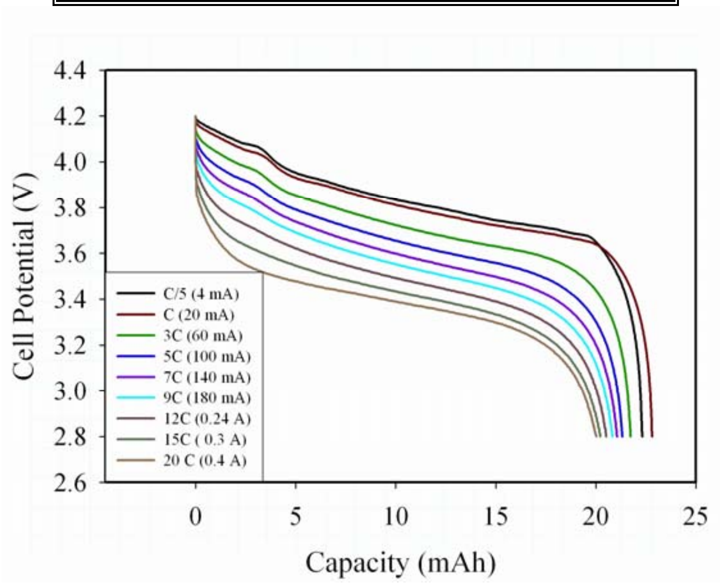
4e. TOBN 150 mAh, 4.5 g Li polymer battery



C-rate	Current (A)	Voltage	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp. Energy (Wh/kg)	Sp. Power (W/kg)
1	0.03	3.75	89	0.1	434	1562	96	25
3	0.45	3.53	120	1.6	424	1525	94	356
5	0.75	3.41	116	2.6	396	1444	88	578
7	1.05	3.3	114	3.5	376	1368	84	778
10	1.5	3.2	112	4.8	358	1282	80	1067
12	1.8	3.15	111	5.7	350	1249	78	1267
15	2.25	3.03	101	6.8	306	1102	68	1511

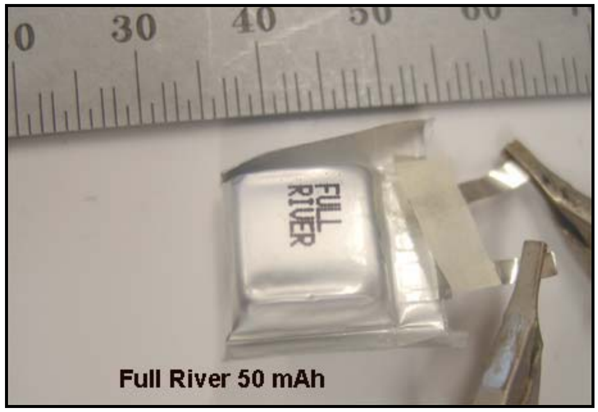
4f. Full River 20 mAh, 0.8 g Li polymer battery

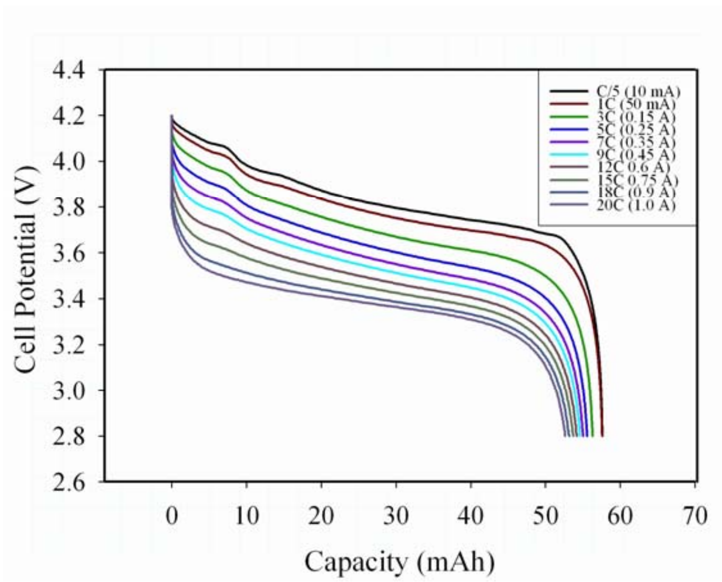




C-rate	Current (A)	Voltage	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp. Energy (Wh/kg)	Sp. Power (W/kg)
1	0.02	3.78	23	0.08	87	313	109	95
3	0.06	3.73	22	0.22	82	295	103	280
5	0.1	3.65	22	0.37	80	289	100	456
9	0.18	3.56	21	0.64	75	269	93	801
12	0.24	3.55	21	0.85	75	268	93	1065
15	0.3	3.46	20	1.04	69	249	87	1298
20	0.4	3.4	20	1.36	68	245	85	1700

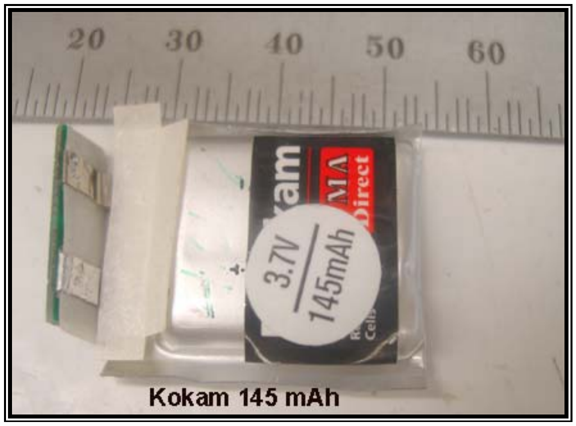
4g. Full River 50 mAh, 1.6 g Li polymer battery

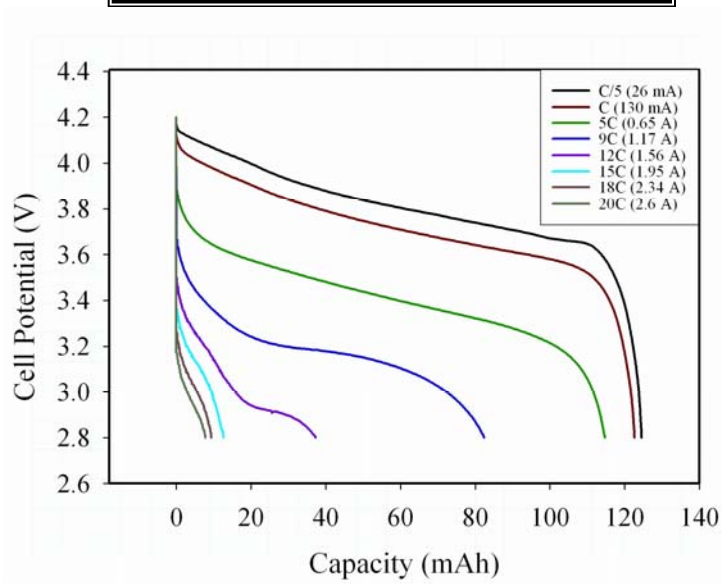




C-rate	Current (A)	Voltage	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp. Energy (Wh/kg)	Sp Power (W/kg)
1	0.05	3.8	58	0.2	220	793	138	119
5	0.25	3.65	56	0.9	204	736	128	570
9	0.45	3.56	55	1.6	196	705	122	1001
12	0.6	3.5	54	2.1	189	680	118	1313
15	0.75	3.48	53	2.6	184	664	115	1631
18	0.9	3.42	53	3.1	181	653	113	1924
20	1	3.4	53	3.4	180	649	113	2125

4h. Kokam 145 mAh, 4.2 g Li polymer battery





C-rate	Current (A)	Voltage	Capacity (mAh)	Power (W)	Energy (mWh)	Energy (J)	Sp. Energy (Wh/kg)	Sp. Power (W/kg)
1	0.13	3.73	123	0.48	459	1652	109	115
5	0.65	3.42	115	2.22	393	1416	94	529
9	1.17	3.20	82	3.74	262	945	62	891
12	1.56	2.80	37	4.37	104	373	25	1040
15	1.95	0.00	0	0.00	0	0	0	0
18	2.34	0.00	0	0.00	0	0	0	0
20	2.6	0.00	0	0.00	0	0	0	0

4i. Physical analysis of Kokam, Full River and Atomic Workshop cells

The batteries tested above are all composed of two long, thin electrodes which are tightly wound, flat around a polymeric separator. Figure 4i-1 shows the positive and negative electrodes coated on aluminum and copper foils, respectively, for a Kokam 145 battery. Each side of the foil current collectors is coated, so the total area of each electrode is about 80 cm^2. Dismemberment of the Atomic Workshop and Full River batteries reveals that they use the same battery electrode configuration as used for the Kokam 145.

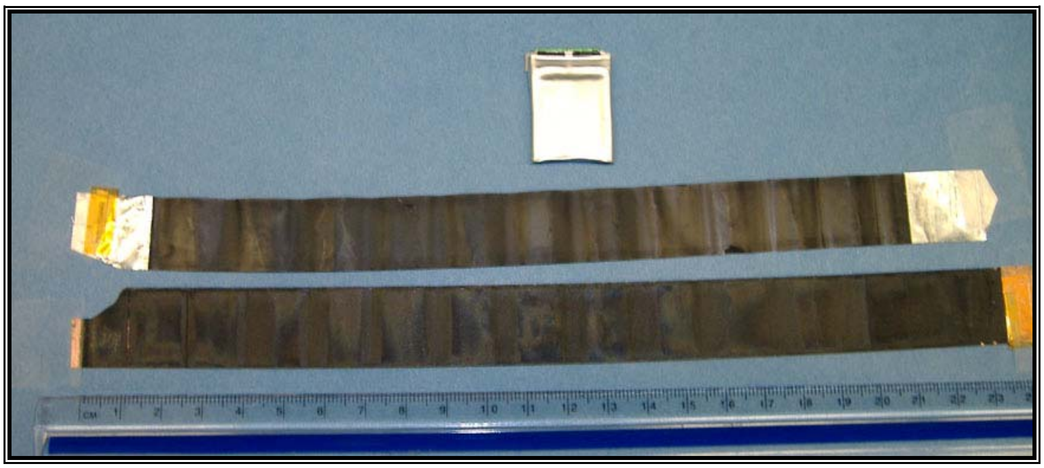


Figure 4i-1. Positive and negative electrodes of a Kokam 145 mAh battery, on aluminum and copper foils, respectively.

Figure 4i-2 shows the SEM images of the active materials in the positive electrodes from Kokam, Atomic Workshop and Full River batteries. They are all a mixture of amorphous carbon and a crystalline, presumably oxide phase. The crystalline particles in the Atomic Workshop and Full River batteries appear less monodisperse than in the Kokam battery.

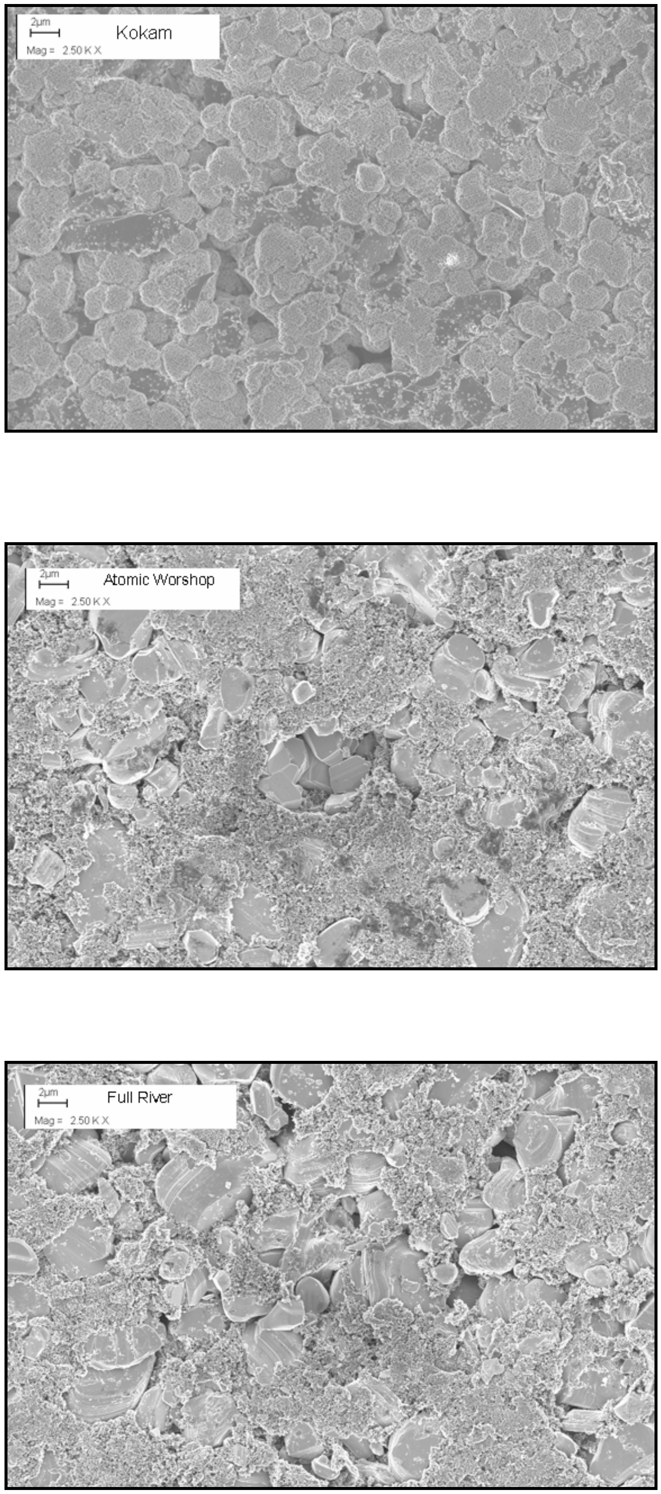
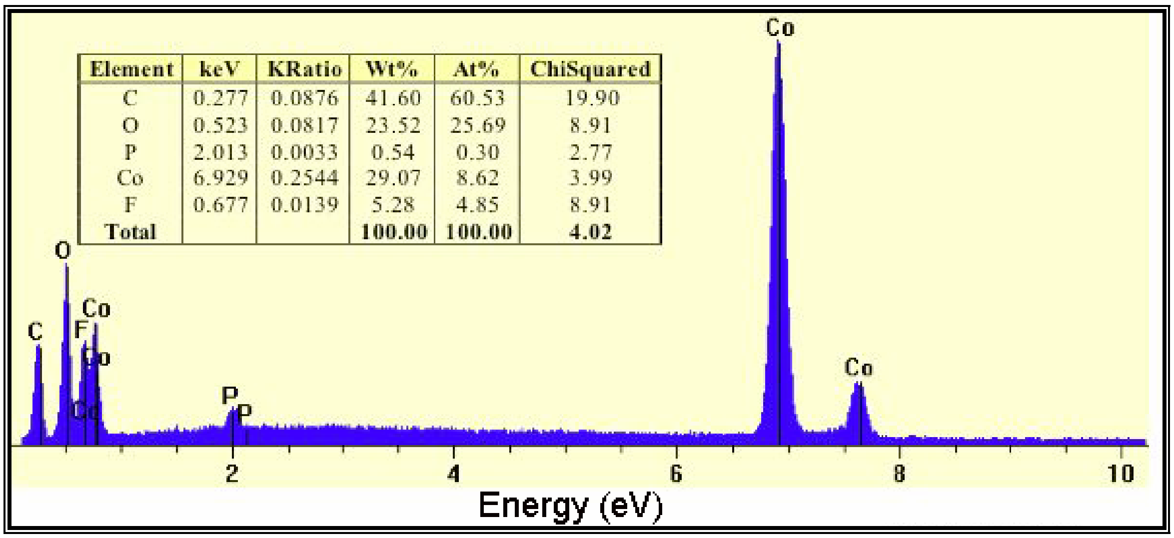


Figure 4i-2. SEM images of the positive electrodes from Kokam, Atomic Workshop and Full River small Li polymer batteries.

Both XRD and EDS results indicate that the cathodes contain $LiCoO_2$. A representative EDS from an Atomic Workshop 130 battery is shown in Fig. 4i-3. The phosphorous and fluorine are presumably from a polyvinylidene fluoride (PVDF) binder or the $LiPF_6$ salt. There is no evidence of Ni or Mn, elements that are sometimes partially substituted for Co in $LiCoO_2$.



Element	keV	KRatio	Wt%	At%	ChiSquared
C	0.277	0.0876	41.60	60.53	19.90
O	0.523	0.0817	23.52	25.69	8.91
P	2.013	0.0033	0.54	0.30	2.77
Co	6.929	0.2544	29.07	8.62	3.99
F	0.677	0.0139	5.28	4.85	8.91
Total			**100.00**	**100.00**	**4.02**

Figure 4i-3. EDS analysis of a Atomic Workshop battery cathode. The chemical analysis is qualitative, as it was not performed with standards.

5. Discussion

5a. Ragone plot of the small Li polymer batteries (specific power vs. specific energy)

The power and energy of the small Li polymer batteries are normalized against their weight in a Ragone plot in Figure 5a based on the data in section 4. The Atomic Workshop 130 mAh battery has the highest specific power of almost 2400 W/kg. The Atomic Workshop 200 mAh battery has the highest specific energy, of 160 Wh/kg, by a small margin. The Full River 50 mAh battery closely competes with the Atomic Workshop 130 and 200 mAh batteries despite its significantly smaller size. This 1.6 g battery may be useful for applications which require a very small battery. Two of the 50 mAh batteries in series may be used as a substitute for one Atomic Workshop 130 mAh battery, in cases where a higher voltage (e.g. ~7 V) is needed.

Only a few years ago, the Kokam 145 mAh battery was a big advance for batteries of this size. Their technology is now outpaced by competitors as manufacturing improvements are made to create batteries with thinner electrodes and less packaging and inactive materials. Improvements in the electrolyte may also be a contributor. Further advances in small Li polymer batteries will likely be made as new materials become available. One such alternate cathode material is carbon-coated lithium iron phosphate, $LiFePO_4$, which will lead to higher power, but lower energy batteries. The driver for battery improvement will continue to be the toy and hobby markets.

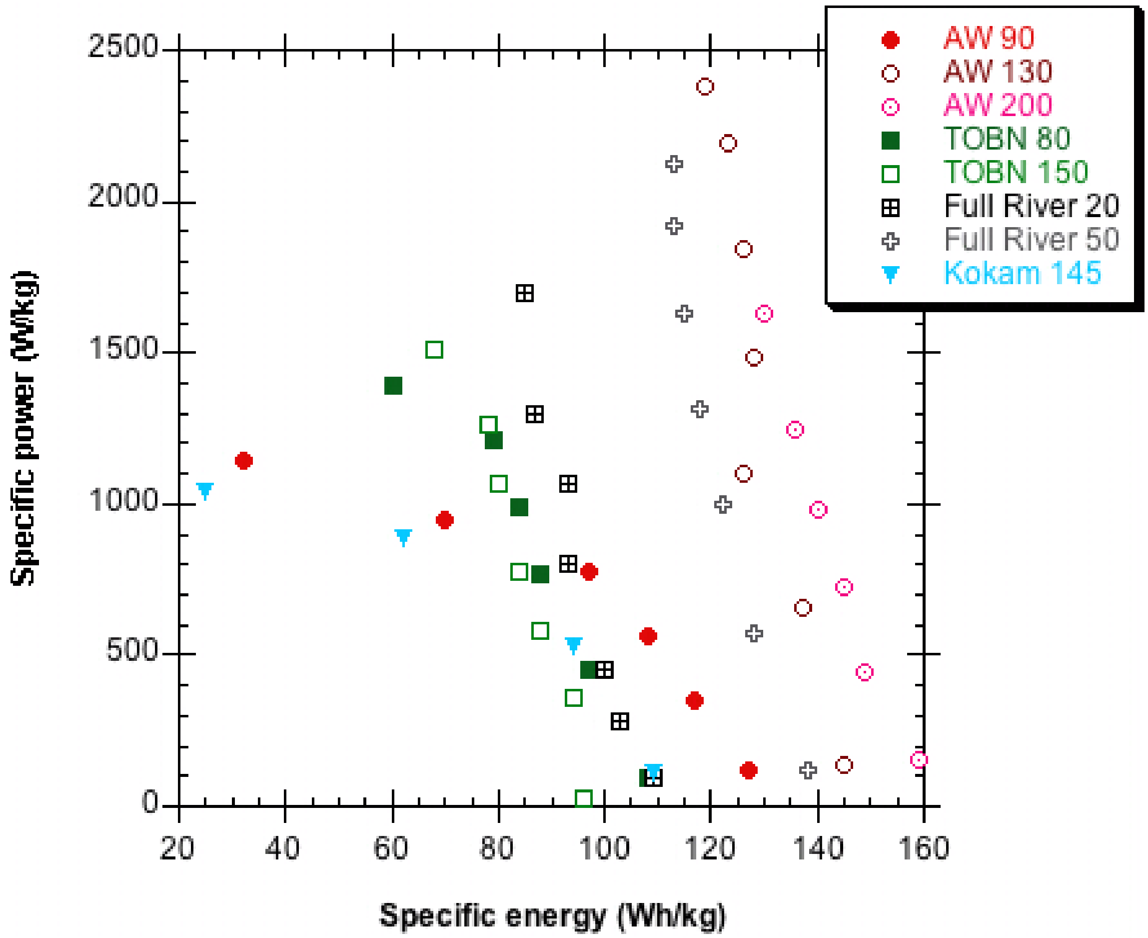


Figure 5a. Ragone plot made from the Li polymer battery discharge data in Section 4.

5b. Power (W) vs energy (J) of the small Li polymer batteries

The power and energy of each battery are given. In general, the heavier batteries have more power and energy; relative differences can be visualized in the Ragone plot in section 5a.

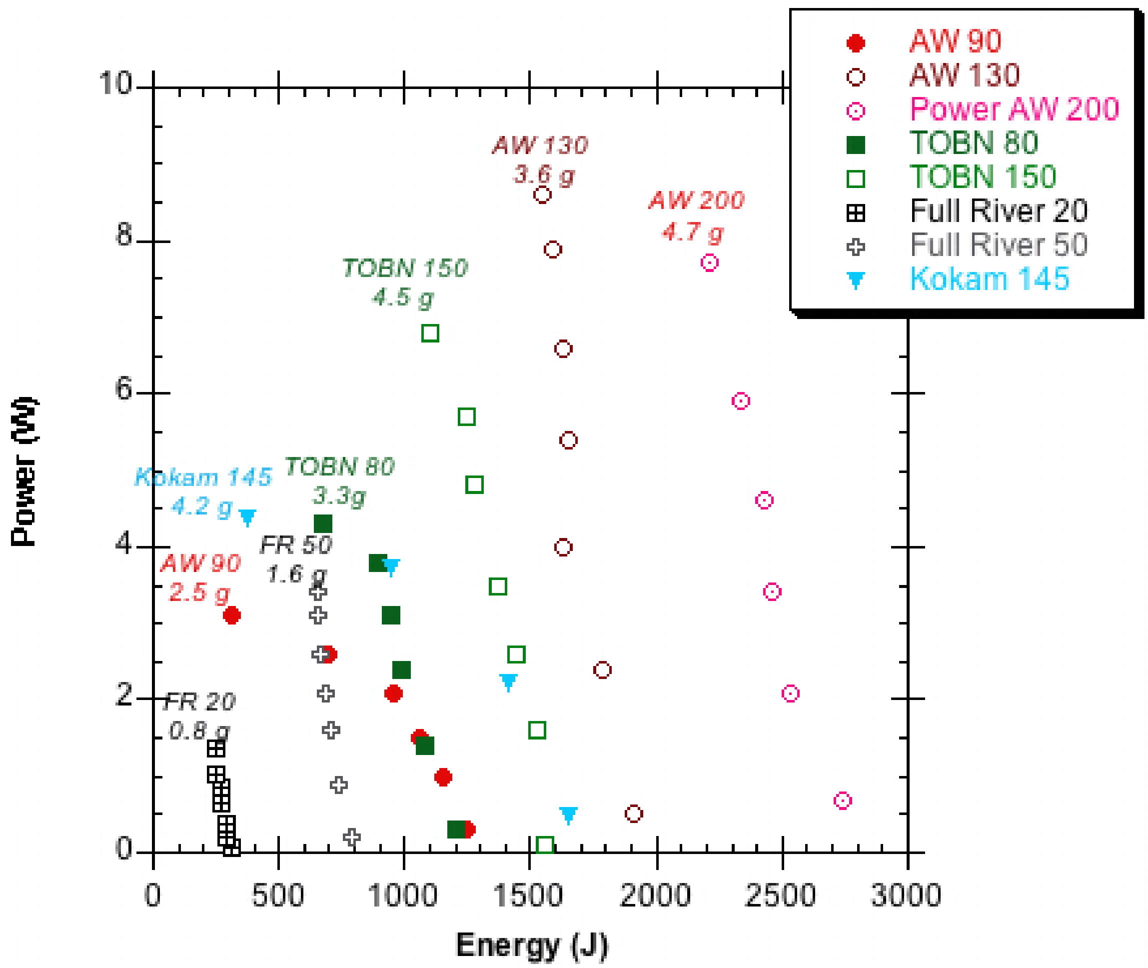


Figure 5b. Power as a function of energy determined from the Li polymer battery discharge data in Section 4.

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